Cardiac MRI

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Introduction

Cardiac MR imaging allows for the examination of anatomy, function, and metabolism and its clinical use is steadily increasing. It poses unique challenges to the imaging protocols as it requires high spatial resolution over a larger volume in the presence of cardiac and breathing motion. This overview of cardiac MRI discusses methods to reduce motion artifacts and various clinical applications including the assessment of cardiac function, dark blood sequences for the visualization of anatomy, cardiac perfusion and viability studies with the administration of a contrast agent, and imaging of the coronary arteries.

Physiological monitoring and gating

The motion of the heart during the cardiac cycle and the motion of the chest during the breathing cycle pose challenges for practically any cardiac MRI scan. Ideally, the data acquisition is completed so rapidly that any physiological motion is 'frozen'. While such realtime imaging sequences based on EPI and spiral sequences have been developed for selected cardiac applications, they do compromise spatial resolution, artifact level, or image contrast in order to achieve the required acquisition speed.

Respiratory Motion

While the average duration of a breathing cycle in an adult is five seconds, the frequency and amplitude of breathing motion can vary significantly from subject to subject. The motion of the diaphragm causes a non-rigid motion of the chest and heart with a predominant component in the cranio-caudal direction of the heart. In order to reduce artifacts from breathing, two approaches are used in clinical practice: (a) completion of the data acquisition in one or more breathholds or (b) extended acquisitions with a simultaneous measurement of the position in the breathing cycle.

Breathhold acquisitions are short and relatively simple to perform. However, they require the ability and corporation of the patient to hold his breath for a given duration, typically between 5 to 20 seconds. Data acquisition can be distributed over multiple breathholds, but artifacts from misregistration might occur because of variations in the actual breathhold position. Even during a single breathhold, drifts of the diaphragm can occur and degrade image quality. Breathholds in expiration are preferred because of a smaller drift. However, patients tolerate longer breathhold durations during inspiration.

Alternatively, the acquisition can be modified according to the position in the breathing cycle as derived from bellows or navigator signals. Bellows measure the tension in an elastic rope over the abdomen of the subject. Data acquisition is then either limited to periods of expiration or the view ordering is adopted to minimize the artifacts from the periodic motion during continuous acquisition. Bellow signals can also be helpful in conforming the motionless durations in breathhold scans. Navigator signals provide more accurate information on the breathing pattern, for example, in coronary imaging. In this approach, the position of the diaphragm is tracked by the analysis of the MR signal from a column placed through the dome of the right diaphragm. While navigators provide higher precision then bellow signals, they do disturb the steady state in a continuous cine acquisition. Both navigator and bellow based respiratory gating prolong total scan time as the scan efficiency is decreased by the rejection of data outside the predefined position window. In addition, drifts in the breathing pattern pose problems. In some applications,

spatial saturation pulses are used to eliminate all signal from moving regions, thereby eliminating artifacts that could originate from these regions.

Cardiac Motion

The motion of the heart during the cardiac cycle is complex and rapid. Therefore, data have to be acquired in short windows in order to minimize motion artifacts. Depending on the application and the heart rate of the subject, these windows are typically 20-150 ms short. Very few sequences can acquire complete images in such short durations. Instead, the acquisition is stretched over multiple cardiac cycles and synchronized with cardiac gating. This approach is referred to as k-space segmentation and is characterized by the views per segment (vps) in each cardiac phase. As an example, let us assume a frame duration of 50 ms and a TR for a single echo acquisition of 5 ms. This sampling scheme has 50/5=10 vps and it would take 128/10 = 13 cardiac cycles to acquire a complete image with 128 phase encoding lines. If the number of views per segment were increased then the total scan time would be reduced to fewer cardiac cycles, but the temporal resolution would also be decreased.

The gating is either based on the signal from a pulse oximeter or from an ECG. While the pulse oximeter can be easily attached to the patient, the R wave in the ECG signal is a much more defined and reproducible marker of position within the cardiac cycle. With prospective gating, the acquisition window starts at a user defined trigger delay after the detection of each R wave. For single phase cardiac imaging, e.g. coronary imaging, a trigger delay is chosen such that minimal motion occurs during the acquisition. In multiphase cine acquisitions, the trigger delay is minimized so that as much of the cardiac cycle as possible can be captured. Alternatively, retrospective gating can be used where data are acquired throughout the complete cardiac cycle and subsequently ordered after scan completion. While this approach allows for a continuous coverage of the cardiac cycle within the steady state, it can not be combined with the use of preparation pulses.

Cardiac Function

MR has become the gold standard in the evaluation of cardiac function. Global functional parameters such as left ventricular volume, mass, and ejection fraction can be readily extracted by identification of endo- and epicardial contours in 2D cine gradient echo acquisitions over multiple slices in the short axis view. In addition, local functional parameters such as wall motion and thickening can be examined. The cine series are typically acquired either with a spoiled gradient echo sequence (SPGR, FLASH, FFE) or a balanced SSFP sequence (FIESTA, trueFISP, bFFE). Whole heart coverage is typically achieved with the acquisition of 2D multiphase short axis slices in multiple breathholds to cover the left ventricle from base to apex. The balanced SSSFP sequence with ultrashort TRs provides T2/T1 weighting and is preferably used because it provides higher SNR, higher contrast between the myocard and the blood pool, and shorter scan times because of the absence of a spoiler gradient. However, the sequence is also receptive to banding artifacts from off-resonance spins, which become more problematic for higher field strengths, poor shimming across the FOV, and for longer TRs, for example in magnets with weaker gradients systems. The spoiled gradient echo sequence, which provides T1 weighted images, is less receptive to off-resonance effects but also shows less contrast between the myocard and the blood pool in the ventricle. In both sequences, fat will generate high signal due to its short T1 relaxation time. For wall motion studies, dobutamine can be administered for stress imaging.

Coronary Imaging

Imaging of the coronary arteries is perhaps the most challenging task in cardiovascular MR. The vessels are small in diameter, their path is tortuous over a larger volume, and their motion

during the cardiac cycle is very complex and varies with the location of the vessel segments. Therefore, a 2D multislice or 3D acquisition with submillimeter spatial resolution and compensation for respiratory and cardiac motion is required. Customized tools such as the 3-point planscan tool have been developed to assist in identifying oblique volumes with minimal dimensions while still covering the desired territory. Data acquisition is typically limited to a period with minimal motion during late diastole. The placement of this time-window of 100ms or less is crucial for the image quality and should be determined patient and vessel specific from a 2D functional cine acquisition. Breathing motion is compensated for by the incorporation of navigator echoes or breathhold acquisitions with small coverage.

Two approaches have evolved for the visualization of the coronary arteries. In black-blood coronary MR, the vessel lumen appears dark due to the use of double inversion pulses with a fast spin-echo sequence as described below. More commonly, bright blood sequences are used with which contrast between the vessels and the surrounding tissues is generated by the inflow effect of unsaturated spins flowing into the imaging slice or slab. In order to enhance this contrast, pre-pulses such as fat-saturation and/or T2-preparation are added to the spoiled gradient echo or balanced SSFP sequence.

Myocardial Viability

The ability to identify dysfunctional yet viable myocardium is crucial for patient care as it predicts the functional recovery following revascularization. MR imaging is becoming the method of choice for the clinical assessment of myocardial viability. Its spatial resolution surpasses the previous gold standard, PET, and allows to identify the transmural extent of myocardial infarction in vivo. Strongly T1-weighted images after the administration of an extracellular Gadolinium-based contrast agent generate delayed hyperenhancement of acute myocardial infarction. Data acquisition is typically based on a spoiled gradient echo sequence with a short TE and TR. An additional 180^0 inversion prepulse is added to invert the magnetization prior to data acquisition, which occurs with a time delay TI (inversion time) to this pulse. Common examples of this sequence type are STIR and FLAIR where the TI is selected to suppress signal from fat or fluids, respectively. Here, the TI is chosen to null the signal of the myocardium for improved image contrast. The optimal TI depends on the interstitial concentration of Gd in the myocardium and varies with the time after the injection. Images can be acquired up to 20 min after the injection of the contrast agent. Typical values for TI range between 170 and 300 ms and need to be identified for each patient with scout scans. The resulting images show no signal in normal myocardium, elevated signal in the blood pool, and high signal in scar tissue. An ECG-gated 2D gradient echo sequence is used for breathhold image acquisition in the short axis orientation and in two- or four-chamber views if the apex is of interest.

Myocardial Perfusion

If a stenosis of a coronary artery occurs, a decrease in myocardial perfusion can be observed prior to clinical symptoms or ventricular dysfunction. With MR, images are acquired very rapidly during the injection of a contrast agent to provide information on myocardial perfusion. This is achieved with ultrafast gradient-echo sequences with a multi-echo acquisition or the use of parallel imaging techniques. Typically, three to seven slices in the short axis orientation are acquired in one or two RR intervals where every slice is acquired in a different stage of the cardiac cycle. Similar to the myocardial viability imaging, magnetization preparation is necessary to improve image contrast. This is accomplished with an inversion recovery, saturation recovery, or notch pulse saturation. Perfusion defects can be more effectively detected under stress conditions induced by the administration of dobutamine or vasodilators such as adenosine. The location and extend of ischemia can then be qualitatively evaluated by

inspection of the time series of the bolus injection. In addition, the data can be analyzed using mathematical models for semiquantitative and quantitative assessment.

Black Blood

Another common technique applied in cardiac imaging is the use of black blood pulses. As the name implies, their purpose is to generate beneficial contrast by nulling the signal in the blood pool. This can be achieved by the use of two consecutive 180⁰ pulses for magnetization preparation. The first of these two pulses is non-slice selective and inverts the magnetization of a large volume. A second slice-selective pulse is then applied soon after to return the magnetization in the imaging slice back to its original position. However, the spins of blood flowing into the imaging slice do not experience the second pulse and are still inverted while and in the process of returning to equilibrium. Data acquisition can then be shifted to the time during the TR when the signal from blood is zero. This sequence is also called the double IR sequence and is most frequently used for TSE sequences, e.g. for anatomical T2 imaging. It can also be combined with a third pulse (triple IR) to suppress signal from fat as well.

Others

While this manuscript focuses on standard clinical applications of cardiac MRI, there are numerous additional techniques investigated and clinically used. One such technique is MR tagging, where saturation bands similar to spatial saturation for motion suppression are adopted that create stripes or a grid across the image. The pulses are played out once at the beginning of the cardiac cycle. The motion of the ventricular wall can then be observed with a cine acquisition and its deformation can be analyzed by dedicated algorithms. Quantitative flow imaging, coronary wall imaging, MR spectroscopy, stem cell tracking, and others are additional protocols of interest in cardiac MR imaging.

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